Europäisches Patentamt

European Patent Office

Office européen des brevets

Bescheinigung

Certificate

Attestation

Die angehefteten Unterlagen stimmen mit der ursprünglich eingereichten Fassung der auf dem nächsten Blatt bezeichneten europäischen Patentanmeldung überein.

The attached documents are exact copies of the European patent application described on the following page, as originally filed.

Les documents fixés à cette attestation sont conformes à la version initialement déposée de la demande de brevet européen spécifiée à la page suivante.

Patentanmeldung Nr. Patent application No. Demande de brevet n°

02079992.0

Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
p.o.

R C van Dijk

Anmeldung Nr:
Application no.: 02079992.0
Demande no:

Anmeldetag:
Date of filing: 29.11.02
Date de dépôt:

Anmelder/Applicant(s)/Demandeur(s):

ASML
De Run 1110
5503 LA Veldhoven
PAYS-BAS

Bezeichnung der Erfindung/Title of the invention/Titre de l'invention:
(Falls die Bezeichnung der Erfindung nicht angegeben ist, siehe Beschreibung.
If no title is shown please refer to the description.
Si aucun titre n'est indiqué se referer à la description.)

Magnetic actuator under piezoelectric control

In Anspruch genommene Prioriät(en) / Priority(ies) claimed /Priorité(s) revendiquée(s)
Staat/Tag/Aktenzeichen/State/Date/File no./Pays/Date/Numéro de dépôt:

Internationale Patentklassifikation/International Patent Classification/
Classification internationale des brevets:

H01L41/00

Am Anmeldetag benannte Vertragstaaten/Contracting states designated at date of filing/Etats contractants désignées lors du dépôt:

AT BE BG CH CY CZ DE DK EE ES FI FR GB GR IE IT LI LU MC NL PT SE SK TR

Magnetic actuator under piezoelectric control.

Field of the invention

The present invention relates to an actuating device for controlling a resultant magnetic force as defined in the preamble of claim 1. Also, the present invention relates to a magnetic actuator for controlling an adjustment force as defined in the preamble of claim 3. Moreover, the present invention relates to a magnetic actuator for controlling a reluctance force as set forth in the preamble of claim 8. Moreover, the present invention relates to a support system as defined in the preamble of claim 13. Furthermore, the present invention relates to a lithographic projection apparatus as defined in the preamble of claim 14. Also, the present invention relates to a device manufacturing method as defined in the preamble of claim 16.

Background of the invention

The present invention finds a preferred application in the field of lithographic projection apparatus that encompass a radiation system for supplying a projection beam of radiation, a support structure for supporting patterning means, which serves to pattern the projection beam according to a desired pattern, a substrate table for holding a substrate; and, a projection system for projecting the patterned beam onto a target portion of the substrate.

The term "patterning means" as here employed should be broadly interpreted as referring to means that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate; the term "light valve" can also be used in this context. Generally, the said pattern will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit or other device (see below). Examples of such patterning means include:

- A mask. The concept of a mask is well known in lithography, and it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. Placement of such a mask in the radiation beam causes selective transmission (in the case of a transmission mask) or reflection (in the case of a reflective mask) of the radiation impinging on the mask, according to the pattern on the mask. In the case of a mask, the support structure will generally be a mask table, which

ensures that the mask can be held at a desired position in the incoming radiation beam, and that it can be moved relative to the beam if so desired;

- A programmable mirror array. One example of such a device is a matrix-addressable surface having a visco-elastic control layer and a reflective surface. The basic principle behind such an apparatus is that (for example) addressed areas of the reflective surface reflect incident light as diffracted light, whereas unaddressed areas reflect incident light as non-diffracted light. Using an appropriate filter, the said non-diffracted light can be filtered out of the reflected beam, leaving only the diffracted light behind; in this manner, the beam becomes patterned according to the addressing pattern of the matrix-addressable surface. An alternative embodiment of a programmable mirror array employs a matrix arrangement of tiny mirrors, each of which can be individually tilted about an axis by applying a suitable localised electric field, or by employing piezoelectric actuation means. Once again, the mirrors are matrix-addressable, such that addressed mirrors will reflect an incoming radiation beam in a different direction to unaddressed mirrors; in this manner, the reflected beam is patterned according to the addressing pattern of the matrix-addressable mirrors. The required matrix addressing can be performed using suitable electronic means. In both of the situations described here above, the patterning means can comprise one or more programmable mirror arrays. More information on mirror arrays as here referred to can be gleaned, for example, from United States Patents US 5,296,891 and US 5,523,193, and PCT patent applications WO 98/38597 and WO 98/33096, which are incorporated herein by reference. In the case of a programmable mirror array, the said support structure may be embodied as a frame or table, for example, which may be fixed or movable as required; and

- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated herein by reference. As above, the support structure in this case may be embodied as a frame or table, for example, which may be fixed or movable as required.

For purposes of simplicity, the rest of this text may, at certain locations, specifically direct itself to examples involving a mask and mask table; however, the general principles discussed in such instances should be seen in the broader context of the patterning means as set forth here above.

Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (e.g. comprising one or more dies) on a substrate (silicon wafer) that has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer will contain a whole network of adjacent target portions that are successively irradiated via the projection system, one at a time. In current apparatus, employing patterning by a mask on a mask table, a distinction can be made between two different types of machine. In one type of lithographic projection apparatus, each target portion is irradiated by exposing the entire mask pattern onto the target portion in one go; such an apparatus is commonly referred to as a wafer stepper or step-and-repeat apparatus. In an alternative apparatus — commonly referred to as a step-and-scan apparatus — each target portion is irradiated by progressively scanning the mask pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the substrate table is scanned will be a factor M times that at which the mask table is scanned. More information with regard to lithographic devices as here described can be gleaned, for example, from US 6,046,792, incorporated herein by reference.

In a manufacturing process using a lithographic projection apparatus, a pattern (e.g. in a mask) is imaged onto a substrate that is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g., an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemical-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or

sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated herein by reference.

For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The radiation system may also include components operating according to any of these design types for directing, shaping or controlling the projection beam of radiation, and such components may also be referred to below, collectively or singularly, as a "lens". Further, the lithographic apparatus may be of a type having two or more substrate tables (and/or two or more mask tables). In such "multiple stage" devices the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposures. Dual stage lithographic apparatus are described, for example, in US 5,969,441 and WO 98/40791, both incorporated herein by reference.

Within a lithographic projection apparatus supports are required that provide a permanent force to oppose gravity. For instance quasi-static supports are required to support an isolated reference frame (which supports the projection system and various sensor devices) and isolate it from external vibrations. Dynamic supports are, for instance, required to support a short-stroke module for a substrate or patterning means on a long-stroke module. In such dynamic supports a static force component is provided to support the weight of the short-stroke module and a dynamic force component is provided to drive the short-stroke module. In both static and dynamic supports it is important that the support bas very low stiffness to prevent the transmission of vibrations.

Previously, it has been proposed to provide a supporting force by means of magnetic attraction and/or repulsion such as, for instance, disclosed in EP 1,001,512 or US 5,780,943. However, the proposed solutions provide a supporting force that may be positional dependent both along and perpendicular to the support direction. The proposed solutions may also be subject to demagnetisation effects.

The support using magnetic force as introduced in the present text is further referred to as an magnetic actuator that provides a magnetic force. The magnetic actuator serves for supporting a load which must be supported and/or positioned at a well-specified position. Typically, the magnetic actuator generates an adjustment force to adjust a position or a compensation force to counterbalance a required force (e.g. gravity).

In the prior art, the actuator is of the so-called Lorentz-type, which uses a magnetic force to keep a load at a well-specified position, or to adjust that position due to a change of the actual load. The generation of the magnetic force by this type of actuator is based on the principle given by Lorentz for the relation between a charged particle, it's movement and an external magnetic field.

Disadvantageously, during the actual operation of the actuator, such an actuator uses an electric current in a conducting coil to generate the magnetic force and at the same time creates a continuous heat dissipation. The heat dissipation may cause a temperature change in the system part in which the actuator is located. The stability of the support may be adversely influenced by thermal drift or thermal expansion (and / or thermal stress) due to a temperature change by the dissipation.

Furthermore, it is noted in case a magnetic actuator from the prior art is to be used for achieving a magnetic levitation of an object, the matter is more complicated since compensating gravity constantly during movement of the object under levitation, requires a continuous change of the phase of the current creating the magnetic field. An increase of that current may cause a demagnetisation effect in the actuator. Also, the dissipation for creating a levitation effect will be relatively large and may cause thermal problems with other parts near the Lorentz actuator(s). Also, during levitation relatively high accelerations may occur in the mechanical parts of the actuator which may cause large disturbance forces and possibly, related damage in those mechanical parts.

Another type for creating adjustment forces is an actuator based on the piezoelectric principle, wherein actuator comprises a piezoelectric crystal and a electrically induced displacement in a piezoelectric crystal is applied to change a position of the actuator. Although their dissipation is small compared to that for Lorentz-type actuators, piezoelectric actuators disadvantageously have a relatively small actuating range, due to the limited value of the piezoelectric effect. Also, piezoelectric actuators are not suitable for creating levitation of an object.

In a continuous effort to create lithographic projection apparatuses with a capability to define patterns with increasingly smaller features, the wavelength of the radiation beam has reduced to increasingly lower values. At present, a typical wavelength is 157 nm, which is in the (deep) ultra-violet part of the electromagnetic spectrum (UV). It is noted that a smaller wavelength in the UV range is possible (e.g., 126 nm) or in the extreme ultra-violet (EUV) in the range of 5-20 nm.

It is observed that the mechanical and thermal stability of the lithographic projection apparatus must remain below values that no influence of heat dissipation by actuators is detected in the performance of the apparatus. By going to increasingly lower values of feature sizes to be exposed and by going to increasingly lower values of the radiation wavelength of the lithographic projection apparatus, the requirements for adjusting actuators with better thermal and mechanical stability increase accordingly.

It is an object of the present invention to provide an actuator which is capable of providing a relatively large force and/or a relatively long actuating stroke, while at the same time the heat dissipation by the actuator is less than detectable relative to the mechanical and thermal stability of the actuator.

This and other objects are achieved according to the invention in a magnetic actuator for controlling a resultant magnetic force on a load as specified in the preamble of claim 1, characterised in that

the magnetic actuator comprises a displacing element attached to at least two of the first, second and third magnetic elements, the displacing element being arranged for changing the magnetic interaction of the first, second and third magnetic elements by relatively displacing at least one of the first, second and third magnetic elements from it's respective position.

Moreover, the present invention relates to a magnetic actuator for controlling an adjustment force as specified in the preamble of claim 3, characterised in that

the first actuating part comprises the first magnetic element and the second magnetic element, the first magnetic element having a third magnetic field and a third magnetic polarisation, the second magnetic element having a fourth magnetic field and a fourth magnetic polarisation,

the first magnetic element and the second magnetic element being arranged adjacent to each other in the first direction and being separated by the first gap distance in between, the displacing element attached to the first magnetic element and to the second

magnetic element, the displacing element being arranged for displacing the first magnetic element relative to the second magnetic element in the first direction to generate the adjustment force in the first direction upon a change of the magnetic interaction by the displacing element between the first and the second magnetic element.

Further, the present invention relates to a magnetic actuator for generating a reluctance force as specified in the preamble of claim 8, characterised in that the magnetic actuator comprises an upper part, a lower part, and an intermediate part, the upper part having the shape of a yoke;
the intermediate part being extended lengthwise in the second direction below the yoke and arranged with a first surface facing a first end surface of the yoke, and with a second surface facing a second end surface of the yoke;
the lower part being located below the intermediate part and comprising a first lower part and a second lower part, the first and second lower parts extending lengthwise in the first direction;
the first lower part being arranged with a third end surface facing a third surface of the intermediate part,
the second lower part being arranged with a fourth end surface facing a fourth surface of the intermediate part;
the magnetic actuator providing, between the first surface and the first end surface and between the second surface and the second end surface, the first gap;
the magnetic actuator providing between the third surface and the third end surface and between the fourth surface and the fourth end surface the second gap distance (GD2);
the intermediate part comprising a fourth magnet with a magnetic polarisation directed in the second direction.

It is a property of this type of magnetic actuator to have low dissipation, i.e., only dissipation during transients and marginal dissipation for control: This feature is present due to the combination of a magnet system with a 'position actuator' i.e. an actuator that has zero dissipation for stationary situations. The magnet system comprises magnetic elements of which the magnetic field is not generated by the Lorentz effect.

Moreover, the present invention relates to a support system as defined in the preamble of claim 13 comprising a magnetic actuator as described above.

Furthermore, this and other objects are achieved according to the invention in a lithographic projection apparatus as specified in the preamble of claim 14, provided with a magnetic actuator as described above.

According to a further aspect of the invention there is provided a device manufacturing method as defined in the preamble of claim 16, characterised by providing a magnetic actuator as described above.

Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The person skilled in the art will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

In the present document, the terms “radiation” and “beam” are used to encompass all types of electromagnetic radiation, including ultraviolet (UV) radiation (e.g. with a wavelength of 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

Brief description of drawings

Below, the invention will be explained with reference to some drawings, which are intended for illustration purposes only and not to limit the scope of protection as defined in the accompanying claims.

Figure 1 depicts a lithographic projection apparatus;

Figure 2 shows schematically a cross section of a magnetic actuator according to a first embodiment of the present invention;

Figure 3 shows a second alternative embodiment of the magnetic actuator according to the present invention;

Figure 4 shows a top view of the magnetic actuator according to a third embodiment;

Figure 5 shows a fourth alternative embodiment of the magnetic actuator according to the present invention for use as a magnetic actuator acting in a substantially horizontal direction;

Figure 6 shows a schematic cross-section of a magnetic actuator according to a fifth embodiment of the present invention for use as piezoelectric actuated reluctance motor;

Figure 7 shows schematically a graph of the resultant magnetic force as function of the position of the moving part of the magnetic actuator according to the fifth embodiment of the present invention.

Description of preferred embodiments

Figure 1 schematically depicts a lithographic projection apparatus 1 according to a particular embodiment of the invention. The apparatus comprises:

- a radiation system Ex, IL, for supplying a projection beam PB of radiation (e.g. UV radiation). In this particular case, the radiation system also comprises a radiation source LA;
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (e.g. a reticle), and connected to first positioning means PM for accurately positioning the mask with respect to item PL;
- a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (e.g. a resist-coated silicon wafer), and connected to second positioning means PW for accurately positioning the substrate with respect to item PL; and
- a projection system ("lens") PL for imaging an irradiated portion of the mask MA onto a target portion C (e.g. comprising one or more dies) of the substrate W.

As here depicted, the apparatus is of a reflective type (i.e. has a reflective mask). However, in general, it may also be of a transmissive type, for example (with a transmissive mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

The source LA (e.g. a mercury lamp or an excimer laser) produces a beam of radiation. This beam is fed into an illumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as σ-outer and σ-inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various

other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

It should be noted with regard to figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being led into the apparatus (e.g. with the aid of suitable directing mirrors); this latter scenario is often the case when the source LA is an excimer laser. The current invention and claims encompass both of these scenarios.

The beam PB subsequently intercepts the mask MA, which is held on a mask table MT. Having traversed the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means PW (and interferometric measuring means IF), the substrate table WT can be moved accurately, e.g. so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means PM can be used to accurately position the mask MA with respect to the path of the beam PB, e.g. after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realised with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed. Mask MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2.

The depicted apparatus can be used in two different modes:

1. In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (i.e. a single "flash") onto a target portion C. The substrate table WT is then shifted in the X- and/or Y-direction so that a different target portion C can be irradiated by the beam PB; and

2. In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", e.g. the Y-direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the

substrate table WT is simultaneously moved in the same or opposite direction at a speed V = M ν, in which M is the magnification of the lens PL (typically, M = 1/4 or 1/5). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

Figure 2 shows schematically a cross section of a magnetic actuator MAC according to a first embodiment of the present invention.

In the magnetic actuator MAC according to this first embodiment, a first, second and third permanent magnet M1, M2, M3 are shown, of which each has e.g., an annular shape arranged symmetrically about a common central axis A1. Between the first and second magnet M1, M2 a piezoelectric element PE is located. The first and second magnets M1, M2 and piezoelectric element PE are combined as a first actuating part MAC1 of the magnetic actuator MAC. The third magnet M3 is part of the second actuating part MAC2.

The piezoelectric element PE is arranged between both magnets M1, M2 in such a way, that the first and second magnets M1, M2 can still be displaced, relative to each other, in a direction parallel to the central axis A1.

The first and second magnets M1, M2 are arranged in such a way that the first magnetic polarisation P1 of the first and the second magnetic polarisation P2 of the second magnet are substantially parallel as designated by the respective arrows P1, P2. Further, the third magnetic polarisation P3 of the third magnet M3 is substantially perpendicular to the direction of the first and second magnetic polarisation P1, P2, as designated by the arrow P3. The magnets M1, M2 , M3 may consist either fully of ferromagnetic material or may be composites comprising ferromagnetic material and a non-magnetic material such as a carbon-based polymer.

Now the effect of the present invention for generating an adjustment force will be explained with reference to Figure 2.

The magnets M1, M2, M3 each comprise a magnetic field surrounding the body of the respective magnet. The first magnet M1 is located with a first end surface at a certain distance G from a second end surface of the second magnet M2 in such a way that there is a gap between the low end surfaces in which the piezoelectric element PE is located.

The resultant magnetic force from the interaction of the magnetic fields of the three magnets is dependent on the relative positions of the three magnets in this embodiment

as will be known by persons skilled in the art: over the gap the magnetic flux of first magnet M1 and the magnetic flux of second magnet M2 interact, yielding in dependence of the actual gap distance, a certain overall magnetic field of the first and second magnets M1, M2. The resultant magnetic force of the three magnets M1, M2, M3 results from the interaction of the overall magnetic field of the arrangement of the first and second magnets (at a given gap distance) in the first actuating part MAC1 and the magnetic field of the third magnet M3 in the second actuating part MAC2.

The relative positions of the three magnets M1, M2, can only be altered by changing the gap distance G.

In a certain position, the magnetic actuator MAC with a load L0 (not shown) coupled to either the first actuating part MAC1 or the second actuating part MAC2, is in a steady state: in other words the net force (the difference between the resultant magnetic force of the magnetic actuator MAC and the force exerted by the load) is substantially zero.

The resultant magnetic force generated in the arrangement of the three magnets M1, M2, M3 counterbalances the force exerted by the load on the part of the magnetic actuator MAC to which the load is attached. In this state, the load is situated at a given position. To relocate the load from this position to one other position, a change of the resultant magnetic force must be generated for relocating the load. The resultant magnetic force can be altered by changing the gap distance G between the first and second magnets M1, M2.

The change of the gap distance causes a change of overall magnetic field of the first actuating part MAC1. When this overall magnetic field changes relative to the magnetic field from the third magnet M3, the resultant magnetic force of the magnetic actuator MAC no longer counterbalances the force by the load.

Depending on the change of the gap distance G, the change of the overall magnetic field of the first actuating part may be such that the resultant magnetic force yields a net force in upward or downward direction. Due to this net force the load L0 will move in the direction of the net force.

As soon as the desired new position is reached the gap distance G between the first and second magnets is changed in such a way that the resultant magnetic force again counterbalances the force due to the load L0. The load will now remain at the newly

chosen position. The relation between force and movement (or position) will be explained later in more detail.

It is noted that a controller (not shown) preferably arranged in a closed loop is to be provided to ensure that the movement of the moving part takes place in a controlled way. The controller comprises a position detector (not shown) which detects the position of the moving part relative to the fixed part of the actuator, and a processing unit (not shown) that reads a position signal from the position detector for determining the position of the moving part of the actuator. Further, the controller is electrically connected (not shown) to the piezoelectric element PE in a manner known to persons skilled in the art. The controller is arranged to control the piezoelectric element PE in such a way that upon reaching the newly chosen position, the dimension of the piezoelectric element in the direction of the gap distance is altered for counterbalancing the resultant magnetic force again with the force due to the load L0. The net force becomes substantially zero by this action of the controller. It is noted that the position detector of the controller may be arranged for detecting a indirect position signal (e.g., a signal related to a magnetic flux) from which a position signal can be derived.

Mechanically, the magnetic actuator MAC has a low stiffness. This means that the magnetic force acting on either MAC1 or on magnet M3 remains almost constant for a displacement (or stroke) of MAC1 relative to M3 (in a vertical direction). A stiffness of ~200N/m (0.2N/mm) can be obtained over a stroke of a few mm. This means that only a small variation in net force is required to displace MAC1 relative to M3. This force variation is realised by altering the gap G. The magnetic actuator force is very sensitive for variations in this gap G: Relatively large force variations occur as a function of a relatively small variation of the gap distance G. A variation in gap distance by 5-6 μm results in a force variation of approximately 0.15 N which is sufficient to move the load over more than 0.5 mm when the stiffness is ~200 N/m.

Since only the piezoelectric element PE needs to be controlled for changing the gap distance to adjust the resultant magnetic force, the dissipation is very low in the magnetic actuator MAC according to the present invention. Advantageously, thermal effects such as thermal expansion and thermal drift can be substantially reduced by the magnetic actuator MAC according to the present invention.

The magnetic actuator MAC is arranged on a base part of the lithographic projection apparatus (not shown) from which an element i.e., a part of the lithographic projection

apparatus, is supported. The magnetic actuator MAC may be attached to the base part by either the first actuating part MAC1 or the second actuating part comprising the third magnet M3.

The base may be attached to a floor part on which the apparatus is installed, in which case the element to be supported could be an isolated reference frame, or the base part may be a dynamic component such as a short-stroke module or a long-stroke module used in a suspension for a gravitational load within the lithographic projection apparatus.

Figure 3 shows a second alternative embodiment of the magnetic actuator MAC. In this embodiment, items are referred to with the same references as in Figure 1 and 2.

In this second alternative embodiment the magnetic elements M1, M2 and M3 again have an annular shape as in the first embodiment. The piezoelectric element PE has an annular shape and is positioned around both first and second magnets M1, M2. The piezoelectric element PE is linked to the first and second magnets M1, M2 by a frame comprising an upper disk B1 attached to an upper end of the piezoelectric element PE and the top outer end of the first magnet M1, and a lower disk B2 attached to a lower end of the piezoelectric element PE and the bottom outer end of the second magnet M2. The third magnet M3 is positioned in between the first and second magnets M1, M2 on one side and the piezoelectric element PE on the other side.

Advantageously, in the second embodiment the working length of the piezoelectric element is larger and the actuating displacement can be larger.

It is noted that the third magnet may also be located in such a way that the piezoelectric element PE is intermediate to the first and second magnets on one side and the third magnet on the other side.

In the second embodiment, the magnet M3 can be connected to the base through holes that are made in the discs B1, B2.

Persons skilled in the art will appreciate that by the use of mechanical elements, such as disks B1 and B2, the stiffness of the arrangement will be increased and result in a damping of the actuating operation. Preferably, application of mechanical elements in the actuator, that may influence the stiffness of the actuator, should be kept to a minimum.

Figure 4 shows a top view of the magnetic actuator according to a third embodiment.

Alternatively, in the third embodiment, in stead of an annular piezoelectric element PE a discrete set of piezoelectric elements can be used in stead of a complete cylindrical PE. e.g., by using two piezoelectric elements and connect these through an upper beam and a lower beam.

In a further fourth embodiment comprising annular magnets M1, M2, M3 with a common central axis A1, the piezoelectric element PE is located in a cylindrical cavity being formed along the common central axis A1 within the first and second magnets M1, M2. The piezoelectric element PE is connected with one outer end to an outer end of the first magnet remote from the gap G and with another outer end to the outer end of the second magnet remote from the gap. The working length of the piezoelectric element PE equals in this fourth embodiment the length of the first magnet, the length of the second magnet plus the gap distance between the first and second magnet. Advantageously, the working length in the fourth embodiment is larger than the working length in the first embodiment, and thus provides a larger actuating range than in the first embodiment.

A further fifth embodiment of the magnetic actuator may be based on the arrangement of the first, second and third magnets M1, M2, M3. In this arrangement in the third magnet M3 an horizontal gap perpendicular to the direction of the central axis is applied. The horizontal gap substantially divides the third magnet in an upper and a lower part. Within the horizontal gap of the third magnet M3 a plurality of piezoelectric elements is present, preferably three piezoelectric elements with an enclosed angle of 120 ° in the horizontal plane between the piezoelectric elements. In this embodiment, the upper part of the third magnet can be tilted relative to the lower part of the third magnet by generating a different displacement for each piezoelectric element within the horizontal gap. This allows generating a couple, perpendicular to the direction of the common central axis, and a resultant magnetic force which can be directed in a direction tilted with respect to the direction of the common central axis A1. In is embodiment, the third magnet M3 may actually be divided in two separate parts, or it may comprise slits within the body of magnet M3 , wherein each slit is arranged for accepting a piezoelectric element.

Finally, it is noted that a further alternative arrangement of the magnetic actuator MAC can have the piezoelectric element PE located within the gap between the first actuating part MAC1 and the second actuating part MAC2.

Figure 5 shows a sixth alternative embodiment of the magnetic actuator MAC for use as a magnetic actuator acting in a substantially horizontal direction. In this sixth alternative embodiment the magnetic actuator MAC is used to produce a displacement in a horizontal direction.

The magnetic actuator of this sixth alternative embodiment comprises two magnetic actuators MAC-A and MAC-B which each comprise first, second and third magnetic elements M1A, M2A, M3A, and M1B, M2B, M3B, respectively, and a piezoelectric element PE-A and PE-B, respectively. The magnetic elements M1A, M2A, M3A, M1B, M2B, and M3B each comprise a magnetic polarisation P1A, P2A, P3A, P1B, P2B and P3B, respectively. Further, the magnetic actuators MAC-A and MAC-B are connected by an connection rod CR. The magnetic polarisation of the first and second magnets of magnetic actuator MAC-A (P1A, P2A) is directed in the opposite direction of the magnetic polarisation of the first and second magnets of magnetic actuator MAC-B (P1B, P2B) to counterbalance the resultant magnetic force of magnetic actuator MAC-A and magnetic actuator MAC-B relative to each other.

The net force for generating a displacement results from the difference in the resultant magnetic force of each of the magnetic actuators MAC-A and MAC-B. In both magnetic actuators the resultant magnetic force can be changed by the piezoelectric element PE of the respective magnetic actuator. (Alternatively, in this sixth embodiment only one of the piezoelectric elements PE-A or PE-B may be present, in the other magnetic actuator the piezoelectric element can be omitted with the first and second magnet in the respective actuator remaining at a fixed position relative to each other.)

The principle of the present invention to generate a resultant magnetic force in response to a piezoelectric actuator, as disclosed above can also be applied in a piezoelectric actuated reluctance motor (or magnetic bearing).

Figure 6 shows a schematic cross-section of a piezoelectric actuated reluctance motor according to a seventh embodiment of the present invention.

The reluctance motor RM consists of a yoke Y comprising a ferromagnetic material. The yoke Y comprises an upper first part Y1, a lower second part Y2, and an

intermediate part Y0 in between Y1 and Y2. The first part Y1 comprises a first subpart Y11, a middle subpart Y12 and a third subpart Y13. The first subpart Y11 is connected to a first end of the middle subpart Y12 under an angle of 90°. The third subpart Y13 is parallel to the first subpart Y11 and is connected to the other end of the middle subpart Y12. The first subpart Y11 at its free end has a slant surface YS1. The third subpart Y13 has a slant surface YS2 at its free end.

Similarly, the second part Y2 of the yoke Y comprises a fourth and a fifth subpart Y24, Y25. Both fourth and fifth subpart Y24, Y25 have a slant surface YS3, YS4, at their respective end directed towards the intermediate yoke part Y0.

The intermediate part Y0 consists of a permanent magnet M4, a first guiding part YC1 and a second guiding part YC2 each with a slant surface YCS1a, YCS1b, YCS2a, YCS2b, respectively, corresponding with the slant surface YS1, YS2, YS3 and YS4 respectively, for guiding the magnetic field of the permanent magnet M4 to the other parts of the yoke. The magnetic polarisation P4 of the permanent magnet M4 is indicated by the arrow P4.

Between the slanted surface YCS1a of the first guiding part YC1 and the surface YS1 of the first subpart Y11 of the first yoke part Y1, and correspondingly, between YCS2a and YS2 a first gap distance GD1 is provided. Also, a second gap distance GD2 is provided between the slanted surface YCS1b of the first guiding part YC1 and the surface YS3 of the fourth subpart Y24 of the second yoke part Y2, and correspondingly, between YCS2b and YS4.

Further, the reluctance motor RM comprises a piezoelectric element PE2, which is connected to the sidewall of the permanent magnet M4 and to the sidewall of the second subpart Y12 of the upper first part Y1 of the yoke.

Below the lower second part Y2 of the yoke, a load (i.e., an object to be lifted to or positioned at a given position under the yoke) is indicated by the reference L0.

The upper first part Y1 and the lower second part Y2 of the yoke are at fixed positions relative to each other. The first part Y1 and the second part Y2 may be connected by a connecting part (not shown) which comprises a material that is non-conducting and non-magnetisable, e.g., a plastic or ceramic.

The intermediate part Y0 of the yoke is arranged for movement in upward or downward direction within the range given by the first and second gap distances GD1, GD2. It is noted that the intermediate part Y0 is arranged in such a way that actual

physical contact to either the upper first part Y1 or the lower second part Y2 is prevented. The magnetic field of the permanent magnet M4 induces magnetic fields in the other parts Y1, Y2, YC1 and YC2 of the yoke Y.

The piezoelectric element PE2 is arranged for changing the first gap distance GD1 and second gap distance GD2 relative to each other. By the actual position of the intermediate part Y0, the first gap distance GD1 and the second gap distance GD2 are set.

The actual magnetic flux (i.e., field strength per unit area) over the respective gap distance is being determined by the ratio between the first gap distance GD1 and the second gap distance GD2. Due to the interaction of the magnetic fluxes, similar as in the first, second, third, fourth, fifth and sixth embodiment of the magnetic actuator MAC as disclosed above, a resultant magnetic force is created which is capable to position the load L0 at a certain given position below the second yoke part Y2. Furthermore, by changing the gap distance ratio through a dimensional change of the piezoelectric actuator PE2, the resultant magnetic force can be varied to change the position of load L0 to either a closer or more distant position relative to the lower second part Y2 of the yoke Y. A person skilled in the art will appreciate that the upper part Y1 of the yoke may be omitted while the magnetic actuator in the seventh embodiment remains still functional: by changing the second gap distance GD2 it is still possible to control the magnetic force acting on the load L0. It is however noted that this control is more complicated to achieve than when the upper part Y1 of the yoke is present and two counteracting magnetic fluxes exist (over the first and second gap distance, respectively): operation of such a magnetic actuator without an upper part Y1 of the yoke is less effective.

In all embodiments as described above with reference to Figures 2, 3, 4, 5, and 6 the change of the resultant magnetic force acting on either the first actuating part MAC1 of the magnetic actuator MAC, or the intermediate yoke part Y0, yields a movement of a moving part of the magnetic actuator.

In Figure 7 the relation between the movement of the moving part of the magnetic actuator and the resultant magnetic force is illustrated with reference to the seventh embodiment. It is noted however, that as is apparent to persons skilled in the art, a similar relation is present for the other embodiments as described above.

Figure 7 shows schematically a graph of the resultant magnetic force as function of the position of the moving part Y2 of the magnetic actuator according to the seventh embodiment.

In this graph the resultant magnetic force is plotted in the vertical direction as a function of the position of the moving part of the actuator in the horizontal direction. The force–position relationship shown here is determined by means of a (finite element method) simulation.

Three function curves were plotted each for a different displacement caused by the piezoelectric element PE, PE2 of the actuator. In this example, the displacement is either nominal, i.e., at steady state position of 0.0 mm, or in this graph, at –0.05 or at 0.05 mm below or above the nominal position, respectively.

The upper function curve represents the force-position curve for a displacement of the piezoelectric element of –0.05 mm.

The middle function curve represents the force-position curve for a displacement of the piezoelectric element of 0.0 mm.

The lower function curve represents the force-position curve for a displacement of the piezoelectric element of +0.05 mm.

The resultant magnetic force is calculated here per meter length of the actuator.

The force response in each function curve is calculated over a range from –0.5 to +0.5 mm for the stroke of the moving part around the nominal position.

Assuming in this exemplary illustration a weight of the moving part and an attached load L0 of 600 N, the magnet of the moving part can be kept at its nominal position. The weight is exactly counterbalanced by the resultant magnetic force.

When the permanent magnet M4 in the intermediate yoke part Y0 moves to, for example, the position of –0.05 mm (upper curve) the attractive force increases to approximately 700 N (for a moving part in a nominal position) and the moving part will move up due to the difference of the resultant magnetic force and the weight: a net force of approximately 100 N acts upon the moving part of the actuator when it is in the nominal position. When the mover moves upwards, the net force will increase even further.

When the magnet moves to, for example the position of +0.5 mm, the attractive force increases to approximately 800 N and the moving part may move up even further

due to the difference of the resultant magnetic force and the weight: a net force of approximately 200 N acts upon the moving part of the actuator.

From Figure 7 it can be deduced that the maximum allowable stroke position is approximately –0.3 mm and +0.3 mm in downward and upward direction, respectively. With a piezoelectric displacement of -0.05 mm (upper curve) below the nominal position (0.0 mm), a resultant magnetic force of 600 N can be generated with the moving part in position -0.3 mm. Note that this is the lowest position in which the load L0 can be retrieved. Below this position, the moving part (and the load L0) can not be stopped any more and will drop. With a piezoelectric displacement of +0.05 mm (lower curve) above the nominal position (0.0 mm), a resultant magnetic force of 600 N can be generated with the moving part in position +0.3 mm. Note that this is the highest possible position. If the load moves higher, it cannot be stopped but will be pulled against the yoke. So, the operational stroke of the moving part is roughly six times larger than the stroke produced by the piezoelectric element. It is noted that the effect of disturbances and accelerations of the moving part of the actuator are not taken in account in the discussion of the maximum allowable stroke. At the maximum allowable stroke, the net force is substantially zero, no force to counteract the disturbance or acceleration is available at that point. The maximum allowable stroke is an upper-bound: the net force must be non-zero to handle accelerations. Consequently, the maximum stroke which allows counteracting accelerations will be smaller than the maximum allowable stroke as described above.

It is noted that optimisation of the working principle for a given size of the magnetic actuator can be focussed on either the actual generated resultant magnetic force or the magnitude of the operational stroke. A trade-off occurs in the combination of force and stroke as will be appreciated by persons skilled in the art. Thus, the principle can be used in one respect for magnetic bearings (large force and short stroke) and in another respect for short stroke motors (small force and comparatively large stroke).

Moreover, it is noted that although the working principle relates to all embodiments shown, the first, second, third, fourth, fifth and sixth embodiments may be more suited for applications comprising small force variations, while the seventh embodiment may be more suited for applications comprising relatively larger force variations. An application for the first, second and third embodiments is e.g., positioning of optical

elements (lenses, mirrors, beam splitters, etc.). An application for the seventh embodiment is e.g., a short-stroke motor or a magnetic bearing.

Finally, the magnetic actuator according to the present invention as described above relates to a translational system. It is noted that the magnetic actuator of the present invention may also be implemented for rotational systems.

Persons skilled in the art will appreciate that other alternative and equivalent embodiments of the invention can be conceived and reduced to practice without departing form the true spirit of the invention, the scope of the invention being limited only by the appended claims.

Claims

1. Magnetic actuator (MAC; RM) for controlling a resultant magnetic force on a load, comprising a first magnetic element (M1; Y0), a second magnetic element (M2; Y1) and a third magnetic element (M3; Y2), the first, second and third magnetic element having a first position, a second position, and a third position respectively,
the first magnetic element (M1; Y0) and the second magnetic element (M2; Y1) being arranged adjacent to each other in a first direction and being separated by a first gap (G1; GD1),
the second magnetic element (M2; Y1) and the third magnetic element (M3; Y2) being arranged adjacent to each other separated by a second gap (G2; GD2) in a second direction,
the resultant magnetic force being a result of a magnetic interaction of the first, second and third magnetic elements at their respective first, second and third position,
characterised in that
the magnetic actuator comprises a displacing element (PE; PE2) attached to at least two of the first (M1; Y0), second (M2; Y1) and third (M3; Y2) magnetic elements, the displacing element (PE; PE2) being arranged for changing the magnetic interaction of the first (M1; Y0), second (M2; Y1) and third (M3; Y2) magnetic elements by relatively displacing at least one of the first, second and third magnetic elements from it's respective position.

2. Magnetic actuator (MAC; RM) for controlling a resultant magnetic force according to claim 1, characterised in that the displacing element (PE; PE2) comprises a piezoelectric element capable, in use, of an electrically induced dimensional change in the first direction for changing the first gap (G1; GD1).

3. Magnetic actuator (MAC) for controlling an adjustment force according to claim 1 or 2, comprising a first actuating part (MAC1) and a second actuating part (MAC2),
the first actuating part having a first magnetic field and first magnetic polarisation

(P1, P2) in the first direction,

the second actuating part having a second magnetic field and second magnetic polarisation (P3) with at least a component in the second direction,

the first direction being substantially perpendicular to the second direction,

the adjustment force being capable of actuating a displacement of the first actuating part (MAC1) relative to the second actuating part (MAC2) in the first direction,

characterised in that

the first actuating part (MAC1) comprises the first magnetic element (M1) and the second magnetic element (M2), the first magnetic element having a third magnetic field and a third magnetic polarisation (P1), the second magnetic element having a fourth magnetic field and a fourth magnetic polarisation (P2), the first magnetic element and the second magnetic element being arranged adjacent to each other in the first direction and being separated by the first gap distance (G1) in between,

the displacing element (PE) attached to the first magnetic element (M1) and to the second magnetic element (M2), the displacing element (PE) being arranged for displacing the first magnetic element (M1) relative to the second magnetic element (M2) in the first direction to generate the adjustment force in the first direction upon a change of the magnetic interaction by the displacing element (PE) between the first (M1) and the second (M2) magnetic element.

4. Magnetic actuator according to claim 3, characterised in that the displacing element (PE) is located in the first gap (G1).

5. Magnetic actuator according to claim 3, characterised in that the first magnetic element (M1) and the second magnetic element (M2) each comprise a cavity extending in the first direction, and that the displacing element (PE) is located inside the cavity of the first magnetic element (M1) and inside the cavity of the second magnetic element (M2),

the displacing element (PE) being coupled with the first magnetic element (M1) and with the second magnetic element (M2), and having a working length substantially equal to the length of the first and second magnetic elements and the distance of the first gap (G1).

6. Magnetic actuator according to claim 5, characterised in that the displacing element (PE) is located adjacent to both first and second magnetic elements (M1, M2),
the displacing element (PE) being coupled with the first magnetic element (M1) and with the second magnetic element (M2), and having a working length substantially equal to the length of the first and second magnetic elements and the distance of the first gap (G1).

7. Magnetic actuator according to claim 6, characterised in that for the coupling to the first magnetic element (M1) a first coupling element (B1) is provided, and for the coupling of the second magnetic element (M2) a second coupling element (B2) is provided.

8. Magnetic actuator (RM) for generating a reluctance force according to claim 1 or 2, characterised in that the magnetic actuator (RM) comprises an upper part (Y1), a lower part (Y2), and an intermediate part (Y0),
the upper part (Y1) having the shape of a yoke;
the intermediate part (Y0) being extended lengthwise in the second direction below the yoke and arranged with a first surface (YC1a) facing a first end surface (YS1) of the yoke (Y1), and with a second surface (YC2a) facing a second end surface (YS2) of the yoke (Y1);
the lower part (Y2) being located below the intermediate part (Y0) and comprising a first lower part (Y24) and a second lower part (Y25), the first and second lower parts (Y24, Y25) extending lengthwise in the first direction;
the first lower part (Y24) being arranged with a third end surface (YS3) facing a third surface (YC1b) of the intermediate part (Y0),
the second lower part (Y25) being arranged with a fourth end surface (YS4) facing a fourth surface (YC2b) of the intermediate part (Y0);
the magnetic actuator providing between the first surface (YC1a) and the first end surface (YS1) and between the second surface (YC2a) and the second end surface (YS2) the first gap distance (GD1);
the magnetic actuator providing between the third surface (YC1b) and the third end surface (YS3) and between the fourth surface (YC2b) and the fourth end surface (YS4) the second gap distance (GD2);

the intermediate part (Y0) comprising a fourth magnet (M4) with a magnetic polarisation (P4) directed in the second direction.

9. Magnetic actuator according to claim 8, characterised in that the second magnetic element (Y1) and the third magnetic element (Y2) are magnets induced by the fourth magnet (M4).

10. Magnetic actuator according to claim 8 or 9, characterised in that the intermediate part (Y0) comprises guiding parts (YC1, YC2) for guiding the magnetic field of the fourth magnet (M4).

11. Magnetic actuator according to claim 8 or 9 or 10, characterised in that the first surface (YC1a) and the first end surface (YS1) are slanted surfaces relative to the first direction, and
that the second surface (YC2a) and the second end surface (YS2) are slanted surfaces relative to the first direction.

12. Magnetic actuator (MAC; RM) according to the preceding claims 1 to 11, characterised in that the magnetic elements comprise non-magnetisable material, such as a carbon based polymer or ceramic.

13. Support system provided with a magnetic actuator (MAC; RM) according to any of the preceding claims.

14. A lithographic projection apparatus comprising:
- a radiation system for providing a projection beam of radiation;
- a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
- a substrate table for holding a substrate; and
- a projection system for projecting the patterned beam onto a target portion of the substrate,

provided with a magnetic actuator according to any of the preceding claims 1 to 12.

15. A lithographic projection apparatus comprising:
- a radiation system for providing a projection beam of radiation;
- a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
- a substrate table for holding a substrate; and
- a projection system for projecting the patterned beam onto a target portion

of the substrate,

provided with a support system according to claim 14.

16. A device manufacturing method comprising the steps of:

- providing a substrate that is at least partially covered by a layer of radiation-sensitive material;
- providing a projection beam of radiation using a radiation system;
- using patterning means to endow the projection beam with a pattern in its cross-section; and
- projecting the patterned beam of radiation onto a target portion of the layer of radiation-sensitive material,

characterised by

providing a magnetic actuator according to any of the preceding claims 1 to 12.

Abstract

Magnetic actuator for controlling a magnetic force on a load, including a first, second, and third magnetic element, the first, second and third element having a first, second, and third position respectively,
the first and the second element being adjacent to each other separated by a first gap in a first direction,
the second and the third element being adjacent to each other separated by a second gap in a second direction,
the magnetic force being caused by a magnetic interaction of the first, second and third magnetic elements at their respective first, second and third position,
wherein the magnetic actuator includes a displacer attached to at least two of the first, second and third elements, the displacer being arranged for changing the magnetic interaction of the first, second and third elements by relatively displacing at least one of the first, second and third elements from it's respective position.

[Figure 2]

Fig 1

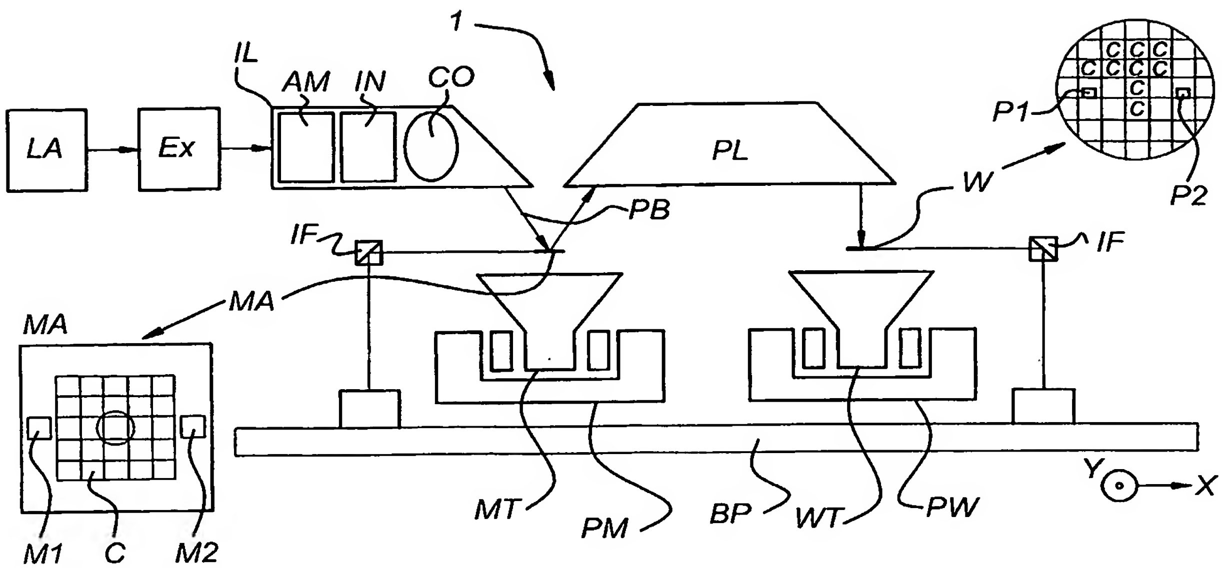


Fig 2

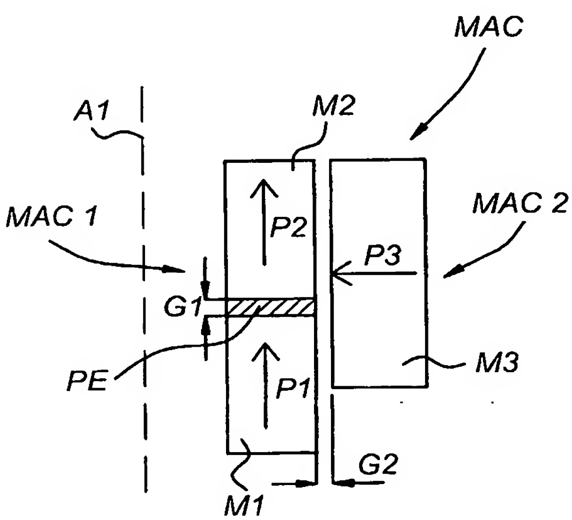


Fig 3

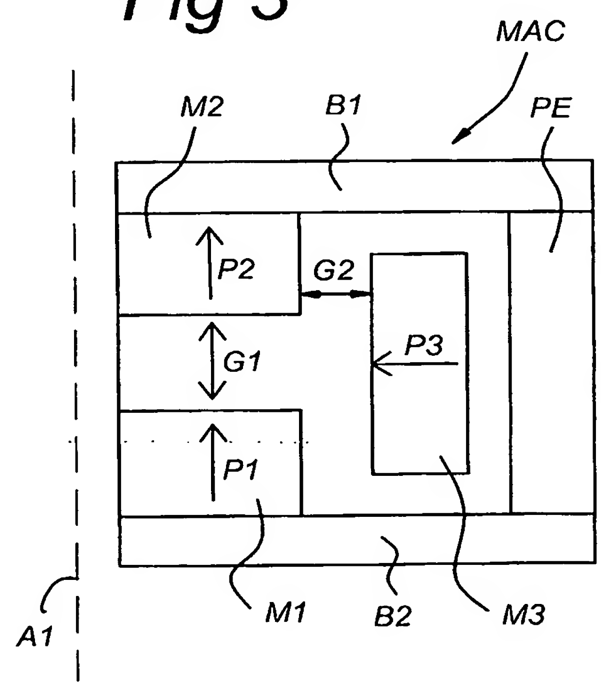


Fig 4

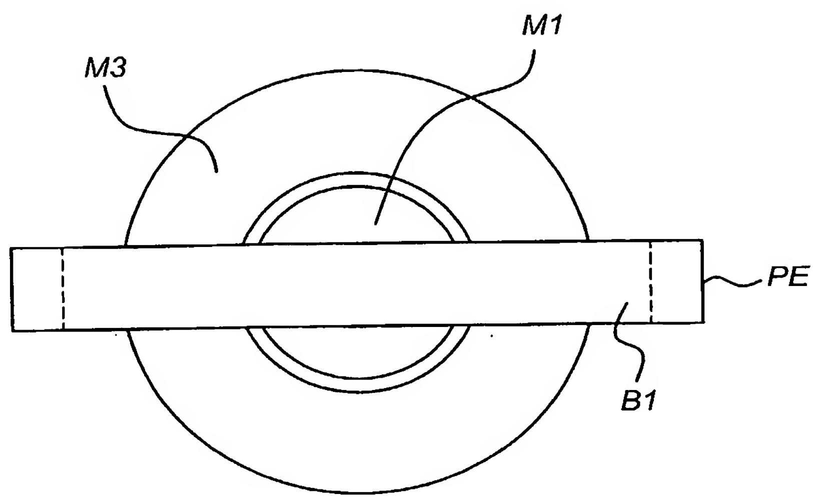

M1
M3
PE
B1

Fig 5

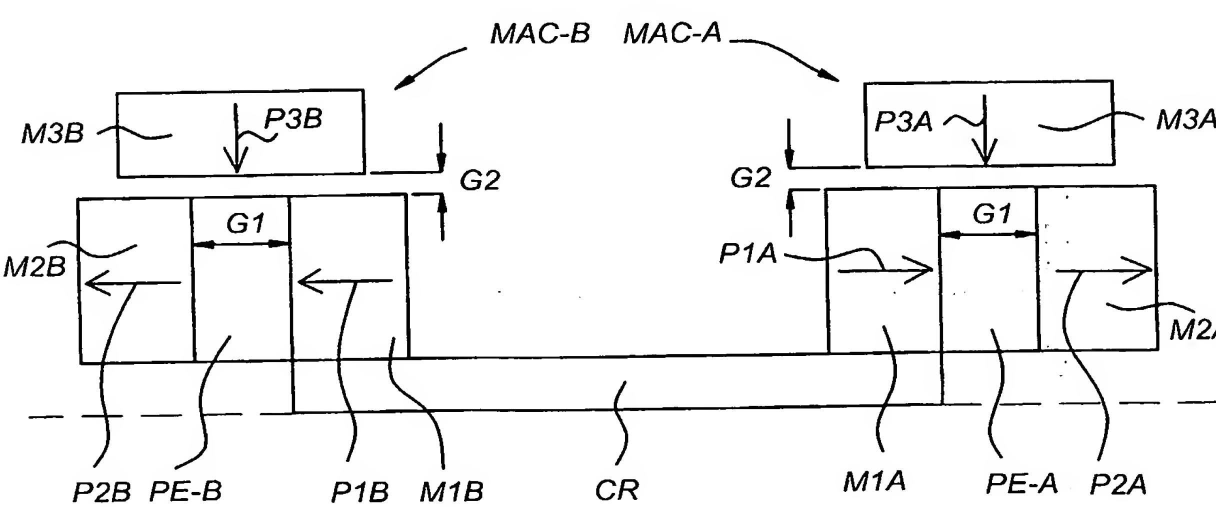

MAC-B
MAC-A
M3B
P3B
P3A
M3A
G2
G2
G1
G1
M2B
P1A
M2A
P2B
PE-B
P1B
M1B
CR
M1A
PE-A
P2A

Fig 6

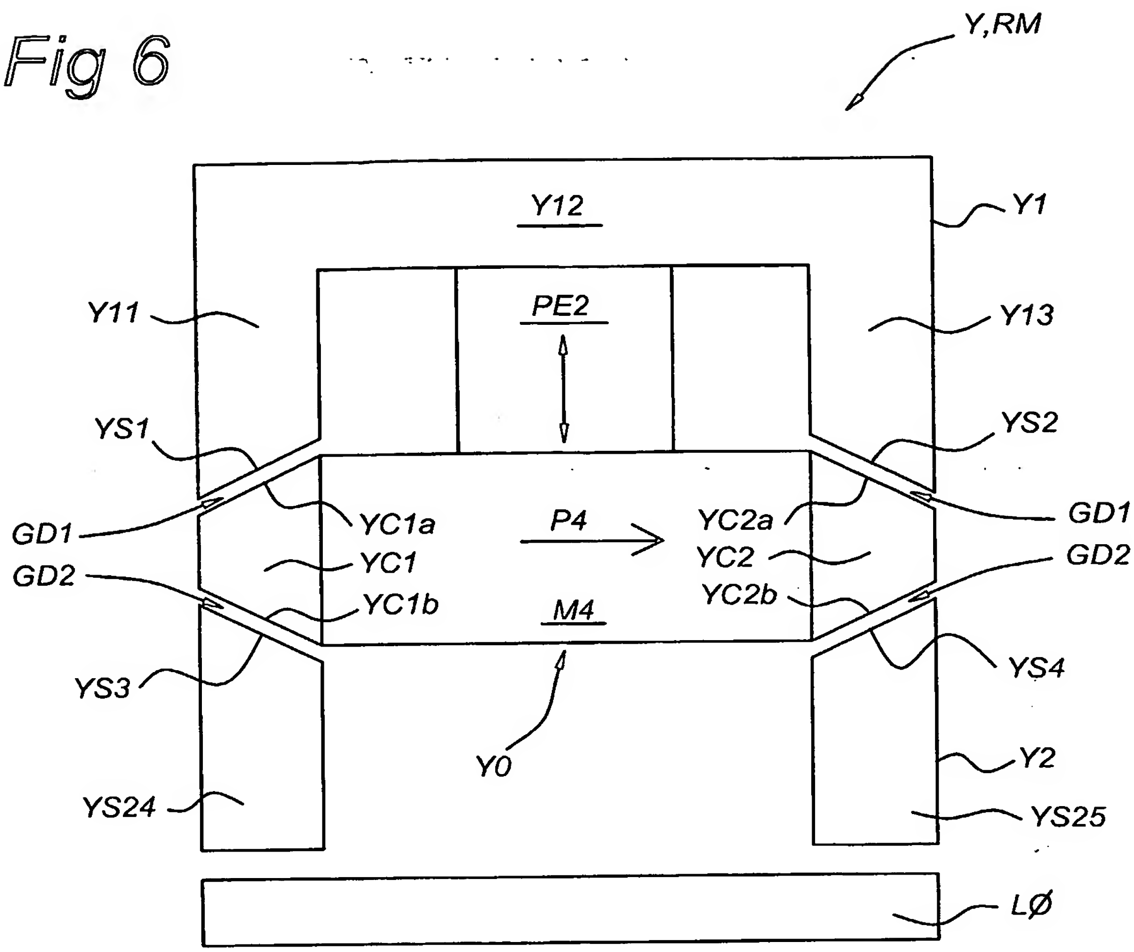
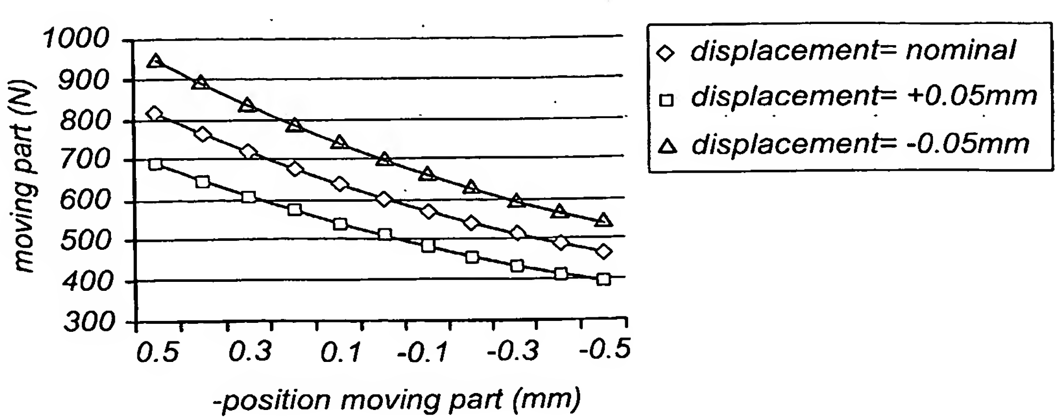

Y,RM
Y12
Y1
Y11
PE2
Y13
YS1
YS2
GD1
YC1a
P4
YC2a
GD1
YC1
YC2
GD2
GD2
YC1b
M4
YC2b
YS3
YS4
Y0
Y2
YS24
YS25
LØ

Fig 7


1000
900
800
700
600
500
400
300
moving part (N)
0.5
0.3
0.1
-0.1
-0.3
-0.5
-position moving part (mm)
displacement= nominal
displacement= +0.05mm
displacement= -0.05mm